FINAL TECHNICAL REPORT FOR GRANT NUMBER: G09AP00053

LABORATORY EXPERIMENTS ON ROCK FRICTION FOCUSED ON UNDERSTANDING EARTHQUAKE MECHANICS

Terry E. Tullis
Tele: (401) 863-3829
FAX: (401) 863-2058
Email: Terry_Tullis@brown.edu

and

David L. Goldsby
Tele: (401) 863-1922
FAX: (401) 863-2058
Email: David_Goldsby@brown.edu

Both at

Brown University
Department of Geological Sciences
Providence RI 02912-1846

May 1, 2009 to April 30, 2010

ABSTRACT

In order to determine where best to deploy limited resources for mitigating earthquake loss in the US, we need to understand when and where earthquakes may occur and how intense their accelerations can be. Every time an earthquake occurs, we gain more understanding of the earthquake problem through measurements of ground motion and modeling of seismic sources. In addition to information derived from earthquakes, we can also benefit from improved understanding of the seismic source through laboratory measurements and modeling, to anticipate what may occur in future earthquakes. One of the great gaps in our understanding of source processes is how shear resistance varies on a fault during seismic slip and what this implies about the magnitudes of stress drops and near-fault accelerations. We are helping to fill that gap through our laboratory experiments.

During this year we have focused on studying the flash weakening mechanism, with only minor work on the gel weakening mechanism and thermal pressurization weakening. For flash weakening, our results, coupled with theoretical estimates of flash temperature, are consistent with flash melting at a sliding speed of 100 mm/s or higher. Constitutive equations for this mechanism are being used in theoretical dynamic rupture models, so it is important that we verify that this mechanism is in fact responsible for the weakening observed in experiments. We have determined which of our several sample assemblies for the Instron apparatus is giving reliable results and have also conducted experiments on flash weakening using a pin-on-disk apparatus at Oak Ridge National Laboratory. Both sets of experiments show that, consistent with theoretical predictions, flash weakening can cause large stress drops over very small amounts of slip and healing is essentially instantaneous. In our planned study of thermal pressurization weakening, another mechanism being used in dynamic rupture models but that has no experimental verification, we have obtained suitable sample materials to use in a planned suite of experiments.

INTRODUCTION

This is a final technical report for USGS grant G09AP00053. The grant covers a one-year period, from May 1, 2009 to April 30, 2010. We have continued work to increase our understanding of flash weakening. The work is relevant to understanding dynamic resistance during earthquakes. We will discuss our progress in detail below.

PUBLICATION RESULTING FROM THIS GRANT

Beeler, N. M., and T. E. Tullis (2010), A Barnes Hut scheme for simulating fault slip, *J. Geophys. Res*, *115*, in press.

Kohli, A. H., D. L. Goldsby, G. Hirth, and T. E. Tullis (2011), Flash weakening of serpentinite at near-seismic slip rates, *J. Geophys. Res.*, *116*, 2010JB007833R, in press.

RESULTS

Background

During the past several years, we have been investigating frictional properties of rocks at nearly seismic slip velocities. Our experiments show that two distinct weakening mechanisms occur at velocities above ~1 mm/s. One of these is a previously unknown mechanism, gel weakening, which operates above 1 mm/s and requires hundreds of mm of slip to be effective. The other mechanism, flash heating of asperity contacts, only operates above 100 mm/s (for many crustal silicate rocks) and only requires fractions of a mm of slip to be effective. Weakening due to thermal pressurization of pore fluids is predicted, but no experiments relevant to this mechanism have been done in spite of our early efforts [*D L Goldsby and Tullis*, 1997].

Weakening via the gel mechanism is so extreme for quartz rocks that our data extrapolate to a strength of essentially zero at a coseismic slip rate of ~1 m/s [*Di Toro et al.*, 2004]. Complete strength recovery at low or zero slip rate after rapid sliding occurs over times of 100 to 2000 s, suggesting that the gel is thixotropic. Although the formation of a silica gel layer explains our observations, further knowledge is required to better understand this mechanism and its applicability to earthquakes, including a better understanding of the roles of water and temperature.

Recent results and insights from high-speed friction experiments

Introduction. Our research efforts of the past year have focused on further understanding and quantifying the frictional behavior of crustal rocks at near-seismic slip rates. We have focused primarily on obtaining a better understanding of dynamic fault weakening due to flash heating of asperity contacts. In the Instron apparatus at Brown, we have used a sample grip that is less compliant and more massive than the grip used in previous tests. As we described in last year's proposal, using this new grip results in negligible oscillations in shear stress due to machine resonance, as has plagued some of our previous tests. We also conducted an extensive series of experiments at Oak Ridge National Laboratory using an established apparatus for studying flash heating, the so-called pin-on-disk (POD) apparatus. These results compliment and corroborate the results obtained using the Instron apparatus, as described below.

Dynamic weakening due to flash heating/melting. At seismic slip rates, high temperatures can be generated at the microscopic contacts on a fault surface, which may thermally degrade the strength of the solid contacts or even melt the contacts, yielding dramatic reductions in fault strength. This 'flash weakening' mechanism is reasonably well understood theoretically, and predictions of macroscopic frictional strength due to flash heating [*Beeler and Tullis*, 2003; *Beeler et al*., 2008; *Rice*, 1999; *Rice*, 2006], employing appropriate physical properties of earth materials with laboratory-like contact dimensions, are apparently in good agreement with data from some high-speed friction experiments on rocks, including those from our laboratory [*Goldsby and Tullis*, 2003; *Goldsby and Tullis*, 2006; *Tullis and Goldsby*, 2003], Vikas Prakash's lab at Case Western University [*Prakash and Yuan*, 2004; *Yuan and Prakash*, 2005], and Toshi Shimamoto's lab [*Hirose*, 2002; *Hirose and Shimamoto*, 2004; *Tsutsumi and Shimamoto*, 1997].

Progress on understanding flash weakening. Within the last year, we have resolved previous technical and other issues that were hampering our efforts at understanding and further exploring flash-weakening phenomena in the Instron testing apparatus. Our problems were centered around two observations – 1) the weakening we measured using both our standard and our new massive sample grips was absent in tests using our newly designed, high-temperature sample grips, and 2) tests on some apparently 'softer' varieties of novaculite yielded no weakening, in contrast to tests on harder, more wear-resistant materials. In the last year, we have confirmed that the lack of weakening in these two situations was due to one or both of two effects – 1) the higher compliance of the high-temperature grips, which contained extra elements (heating and insulating blocks), and 2) the use of a softer variety of novaculite, which resulted in the generation of a finite thickness of uniformly shearing gouge. We believe shearing of a finite thickness of gouge may have shifted the flash weakening velocity to sliding rates unattainable in the Instron apparatus. We have conducted new tests using the massive sample grip wherein we replaced the novaculite with a wear-resistant hard quartzite to eliminate the effects of gouge development on flash weakening behavior. These changes have yielded the best available data on flash weakening behavior in rocks. We have also conducted new tests on serpentinite using the massive sample grip.

New results on quartzite - Results of a series of tests on hard quartzite are shown in Fig. 1. We conducted two types of test on the quartzite – continuously varying-velocity (hereafter termed CVV for brevity) tests, and velocity-stepping (VS) tests. Fig. 1a shows the results of one of the CVV tests,

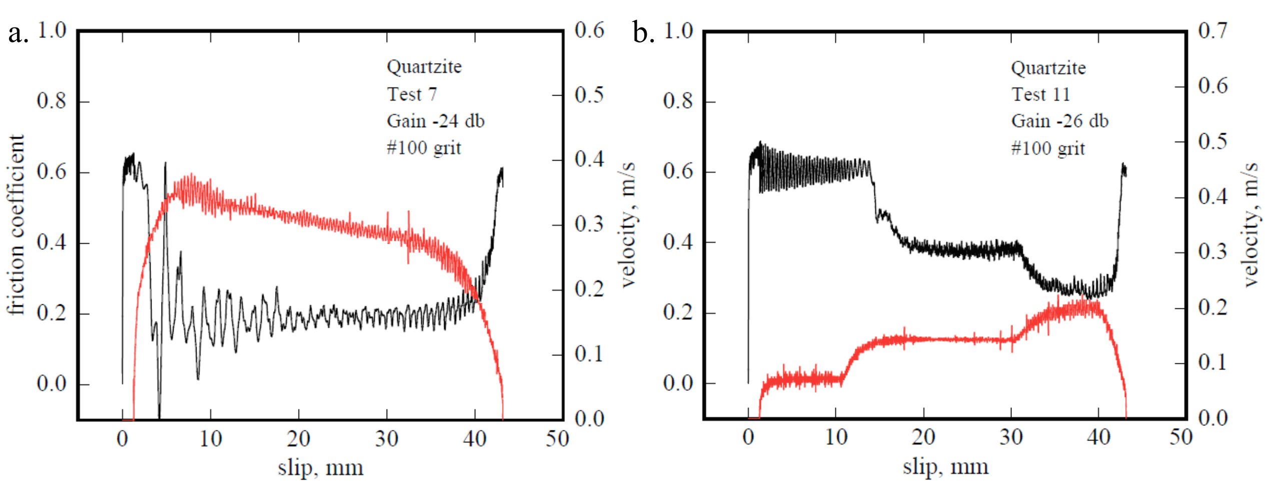

Figure 1. Examples of a) continuously varying velocity (CVV) test on quartzite and b) of a velocity-stepping (VS) test on quartzite. The velocity data are shown in red, the friction data in black.

wherein the velocity peaked at a value of ~360 mm/s near the beginning of the test, decreased slowly during most of the slip, then decreased rapidly to zero at the end of the test. In Fig. 1b, the results of a VS test on quartzite are shown. In the VS tests, we attempted to produce step changes in velocity over a range of rapid sliding speeds. At each step change in velocity, friction is observed to change to a new value characteristic of the new slip rate.

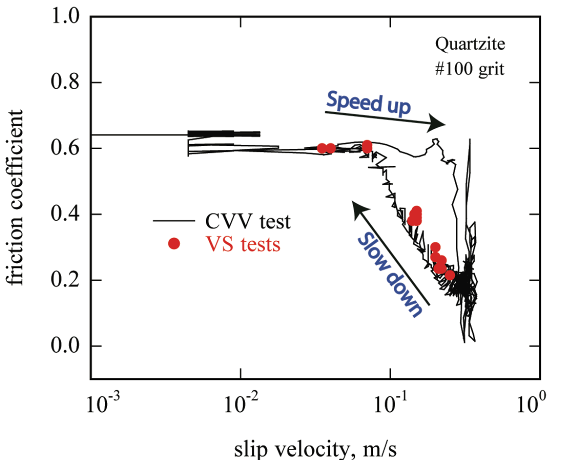

Figure 2. Comparison of data from constantly varying velocity (CVV) tests with those from velocity-stepping (VS) tests on quartzite. Note hysteresis in the data from the CVV test.

In Fig. 2, we plot friction as a function of continuously varying slip rate from Fig. 1a (solid black trace in Fig. 2) along with discrete values of friction at each slip rate from the VS tests of Fig. 1b (red data points in Fig. 2). Note that there is a marked hysteresis in the friction vs. velocity trace of Fig. 2, with the value of friction for a given velocity above the weakening velocity (~100 mm/s) during speed-up reaching higher values than for the friction data obtained at the same velocity during slow-down. As shown in Fig. 2, the friction vs. velocity data points from the VS tests are in excellent agreement with the data in the slow-down portion of the CVV tests. This strongly suggests that the slow-down portion of the friction vs. velocity data in the CVV tests is a more accurate representation of the actual material behavior than the speed-up data.

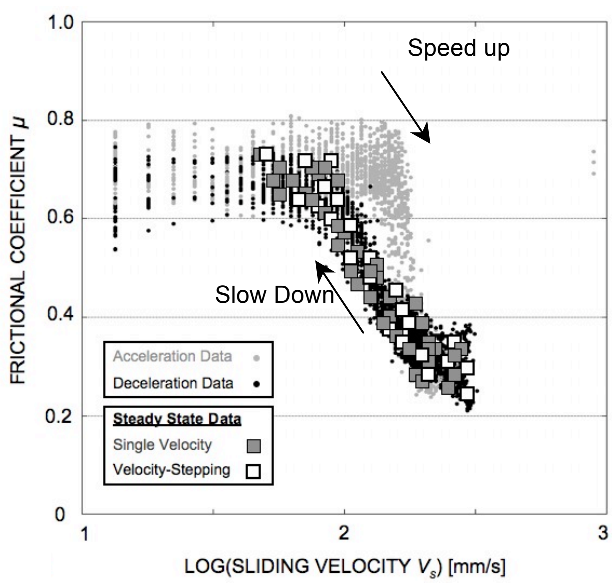

Figure 3. Plot of data from CVV and VS tests on serpentine. Data from accelerating portions of the CVV tests are shown by the small gray data points, from decelerating portions of the CVV tests by the black data points. White and dark gray square data points are from single-velocity tests and VS tests.

New results on serpentine – We have continued to explore the frictional behavior of serpentine, with implications, amongst others, for the occurrence of earthquakes on oceanic transform faults. These experiments were not identified in our earlier proposals as specific areas of focus, but evolved out of an ongoing collaboration with Prof. Greg Hirth at Brown, and Arjun Kohli, a talented, Stanford-bound Brown undergraduate. The work described below is funded in part by research grants directed by Prof. Hirth and by a Brown undergraduate research grant for Arjun Kohli. Funding for the collaboration and expertise of David Goldsby, and for experimental materials and supplies, is provided by our USGS grant.

As for the tests on quartzite, the experiments on serpentine reveal a dramatic weakening behavior consistent with flash weakening. Figure 3 is a plot of friction vs. velocity from such tests, which shows the nearly purely velocity-weakening behavior characteristic of flash heating. As for quartzite, the decelerating portion of the CVV tests yields data that are in excellent agreement with 'steady-state' data from the VS tests. X-ray diffraction of the gouge products on the slip surface reveal the presence of talc, a reaction product of serpentine dehydration at elevated temperatures, for samples slid at velocities greater than ~100 mm/s. Samples deformed at slower slip rates did not show the presence of talc. Finally, scanning electron microscopy of the slip surface reveals raised areas tens of microns in diameter, the contact sizes inferred to be required to produce temperatures high enough to induce dehydration of serpentine at asperity contacts, based on the serpentine phase diagram and flash weakening theory.

These data suggest that slow slip on faults containing serpentine, such as transform faults or the San Andreas Fault, is stable to earthquake nucleation, but that propagation of dynamic ruptures into serpentinized zones may trigger unstable slip in these areas. The results of these experiments are reported in a paper now in press [*Kohli et al.*, 2011].

Hysteresis. Comparison of our new results from VS tests on quartzite with those from CVV tests on quartzite suggests that the true velocity dependence is given by the slow-down part of the hysteresis loop in our friction data, as in Fig. 2 and 3. We do not yet understand why friction at a given velocity is higher on speed-up. Figure 4 shows a plot of friction vs. velocity for both VS tests and CVV tests on quartzite. As can be seen in the figure, the magnitude of the rightward shift of the data on speed-up scales with the magnitude of the velocity step. This suggests that the speed-up data are not an intrinsic property of the material, but depend on the experimental details, unlike the slow-down data, and may be related to inertial effects.

In an attempt to better understand the cause of the hysteresis in these tests in the Instron, we installed a Rotary Variable Displacement Transducer (RVDT) to measure the rotation of the lower sample grip as close as possible to the sliding surface. We surmised that inertial effects might cause the sample to lag in slip and slip velocity at the beginning of a test or at a velocity step compared to the load point velocity (at the rotary actuator), the variable we plot as 'slip velocity'. An RVDT is akin to a Linear Variable Displacement Transducer (LVDT), often used to make linear measurements of displacement, but the RVDT instead measures rotary motion. This measurement was made by placing a rubber wheel mounted on the RVDT shaft against the lower sample grip. However, within experimental error we cannot yet detect any lag in the sample velocity relative to the plotted load point velocity. Consequently, we are still unclear as to what causes the speed-up friction to obtain higher values than the slow-down data.

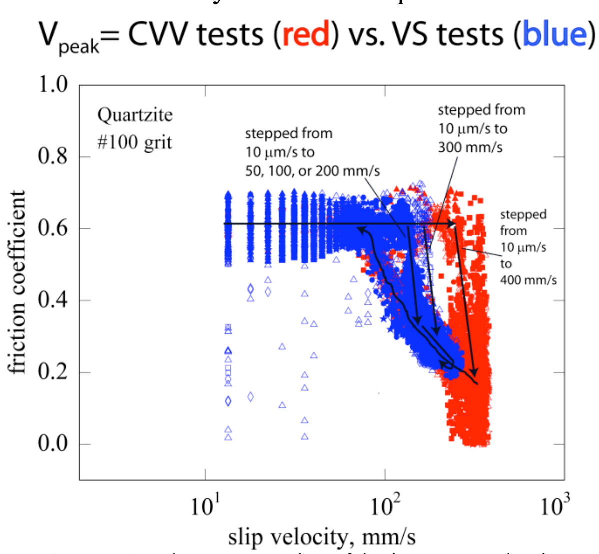

Figure 4. Plot comparing friction vs. velocity for CVV and VS tests. The magnitude of the rightward excursion in the data scales with the magnitude of the velocity step, highlighting the possible role of inertia. Arrows indicate the data paths on speed up and slow down.

Tests in the Pin-on-Disk Apparatus

In February 2010, one of us (DLG) traveled to Oak Ridge National Lab to conduct tests using a high-temperature, controlled-atmosphere pin-on-disk (POD) apparatus in Dr. Peter Blau's Tribology Center. The POD test has classically been used to study flash weakening behavior in metals and other engineering materials, and analytical solutions exist for calculating the frictionally generated temperature of the contact [*Lim and Ashby*, 1987]. The boundary conditions for a POD test are different and somewhat more complicated than in a typical rock-friction test. In a rotary-shear rock-friction test, for example, cumulative slip at any point on either of two opposing surfaces in contact (assuming bare surfaces or localized slip in gouge) is just the cumulative sliding displacement. In the POD test, the accumulated slip on the surface of the pin is also equal to the total sliding displacement. The accumulated slip at a given point in the sliding track on the disk, however, is much less and equal to the contact size times the number of revolutions of the disk. Thus, care is required in drawing conclusions about the effects of cumulative slip on frictional behavior when the POD is used. The POD test is well suited for studies of flash heating, however, since the pin is continually abraded, exposing fresh material that slides against a surface that has undergone relatively minor damage. We believe this feature allows for an accurate assessment of the role of contact size, for example, on the flash weakening velocity.

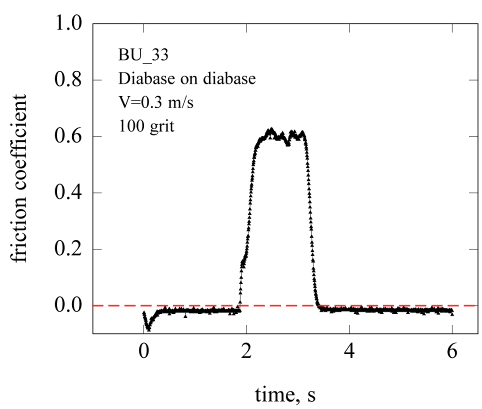

Figure 5. Data from a so-called drop test in the POD apparatus on diabase. Dashed red line is the nominal zero point before and after the test.

We conducted preliminary tests on 4 geologic materials – quartz, dunite (olivine rock), calcite and diabase. A sample consisted of a pin about 2 cm long and 1 cm in diameter, slid against a square disk about 15 cm^2 in area. Pins were prepared with quasi-hemispherical ends by grinding the ends of rotating cylinders of the various rocks with a Dremel tool. Disks with prescribed surface roughness were prepared by surface grinding and roughening with wet grit on a glass plate. The first test suite was designed to make a broad survey of the effects of sliding velocity and temperature on the measured friction.

We devised two types of POD test. In the first, the pin was placed in contact with the disk under a known dead-weight load at zero slip velocity, and the motor that rotates the disk was then switched on and the disk was rotated at a constant slip rate. In the second, we spun up the disk to a constant rotation rate with the pin out of contact with the disk, then manually lowered the dead-weight-loaded pin onto the disk and then quickly raised the pin out of contact, with the loading and unloading cycle lasting for 2 or 3 seconds. An example of the experimental results from this second type of test is shown in Fig. 5. Unlike the first test, the second test allowed us to measure friction with only minimal damage to the surface and avoided complications due to not knowing the actual slip rate in the earliest part of the first type of test.

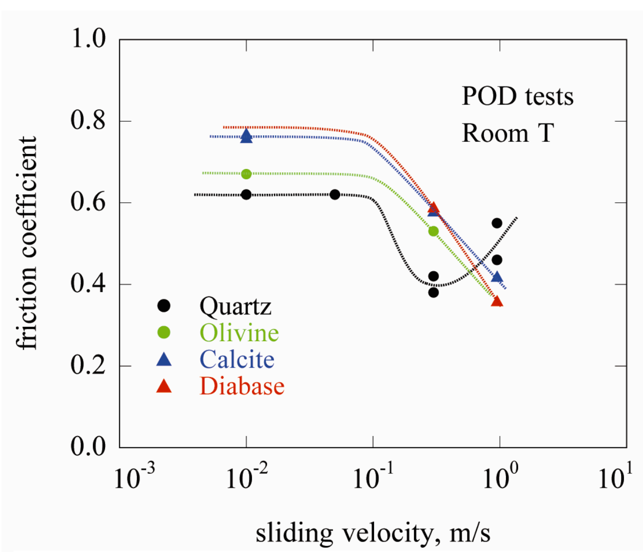

Figure 6. Plot showing the measured friction coefficient (data points) vs. slip rate from POD tests. Trends are inferred on the basis of the assumption that weakening results from flash heating.

Velocity dependence of friction – All of our POD experiments revealed a marked dependence of friction on slip rate, as is shown in Fig. 6. Tests on calcite, olivine, and diabase showed continuously decreasing values of the friction coefficient over the range of velocities investigated; the data for quartz indicate velocity weakening behavior with increasing slip rate to 0.3 m/s, and velocity strengthening behavior from 0.3 to 0.95 m/s. A slip rate of 0.95 m/s is faster than any sliding velocity we have ever explored in flash-weakening experiments, so the results for quartz are not unusual compared to previous results. We note that some theoretical treatments of flash melting predict such a transition to velocity strengthening at high slip rates above the weakening velocity [*Rempel and Weaver*, 2008]. ‘Strengthening occurs beyond a threshold sliding rate above which further increases in slip speed shorten the contact lifetime enough that the corresponding increase in heating rate can't thicken the film fast enough to cause further weakening - the average asperity strength is predicted instead to increase’ (Rempel, personal communication, 2010). To further investigate this intriguing behavior, additional experiments are required to more completely map out the friction vs. velocity trend suggested by Fig. 6. Such an increase in friction at seismic slip rates would have critical implications for dynamic rupture.

Comparison of data acquired with the POD and the Instron – In Fig. 7, we compare data from the POD tests with those from the Instron tests for two materials – quartz and diabase/gabbro. For the case of quartz (Fig. 7a), the tests at the highest slip rate, 0.95 m/s, yield an apparently higher value of friction than the Instron tests at up to 0.4 m/s. The weakening velocity for quartz determined in the POD tests is also inferred to be slightly higher than for the Instron tests, though more experimental data are required to firmly establish the trend in the POD tests. For the case of the diabase/gabbro (Fig. 7b), the weakening velocity from the POD tests on diabase is also slightly higher than in the case of the Instron tests on gabbro, and no increase in friction is observed at 0.95 m/s as occurs for quartz in the POD tests. Thus, the favorable comparison of the data sets lends even further support for the occurrence of flash weakening in the Instron experiments.

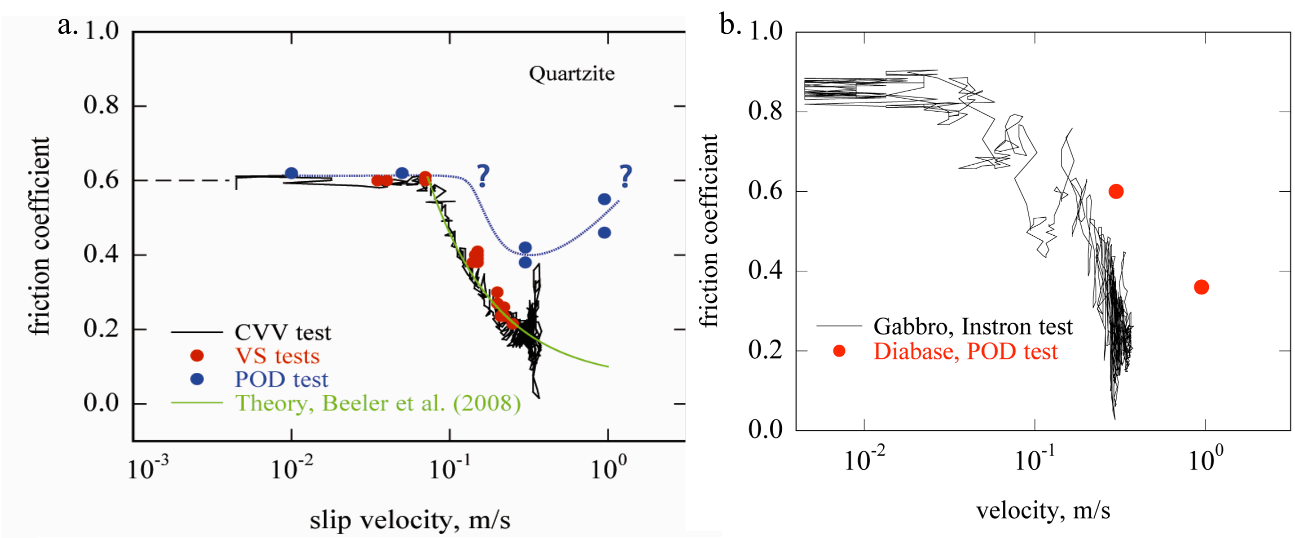

Figure 7. Comparison of data from POD tests with those from tests in Instron apparatus. a) Comparison of quartz POD data (blue dots) with those from CVV tests (solid black line) and VS tests (red dots) in the Instron. Dashed blue line shows inferred trend of the POD data. The solid green trace is a theoretical expression of flash weakening behavior from *Beeler et al.* [2008]. b) Comparison of data from Instron tests on gabbro (solid line) with POD tests on diabase (red dots).

Temperature dependence of friction – A testable prediction of flash weakening theory [e.g., *Rice*, 2006] is that the weakening velocity should decrease with increasing average temperature of the fault surface. Theory predicts that the weakening velocity $V_w \propto [(T_w - T_f)/\tau_c]^2$, where T_w is the weakening temperature, T_f is the slowly evolving average temperature of the fault surface, and τ_c is the contact shear stress. All but the calcite rocks in the POD apparatus were tested at room temperature and 500 °C. The calcite samples had to be tested at room temperature and 300 °C, since calcite samples decomposed at 500 °C. All of the rocks tested showed decreases in friction at a given slip rate above the estimated weakening velocity with increasing temperature. From the expression above, an increase in temperature to 500 °C is expected to cause a decrease in the weakening velocity by a factor of ~2 (assuming a weakening temperature of 1500 °C, and neglecting the assumed small decrease in contact stress with increasing temperature; a weakening temperature of 1000 °C yields about a factor of 4 change in friction). At this time, we have insufficient data (i.e., incomplete trends of friction vs. sliding velocity at various temperatures) to accurately quantify the shift in the weakening velocity with temperature. However, as suggested by the data in Fig. 8, estimated $1/V$ trends of friction with velocity for olivine at 25 and 500 °C suggest decreases in V_w by a factor of ~5, comparable with the expected estimate given above.

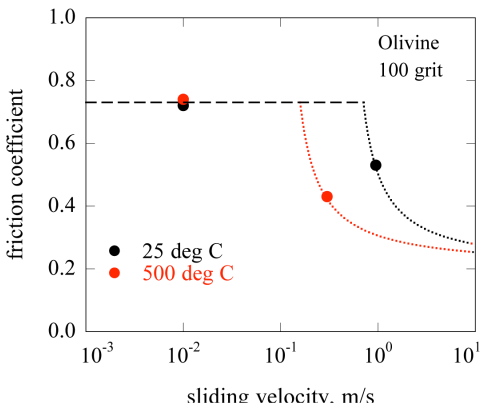

Figure 8. Inferred dependence of weakening velocity on average sliding surface temperature T_f for olivine (see text for explanation).

Dynamic weakening due to silica-gel lubrication – During the past year we have not focused on this weakening mechanism, because of our primary focus on the flash weakening mechanism and setting up to resume our experiments on thermal pressurization. The use of high-temperature grips in the Instron will be key to some of our planned gel weakening experiments. During the past year we have conclusively shown that the massive Instron grips are the best design and our first generation of high temperature grips are unsatisfactory. Thus, it made no sense to use these unsatisfactory grips; we will design and construct a modified massive grip that incorporates heating elements. We will use this grip to conduct high-temperature experiments.

Dynamic weakening due to thermal pressurization of pore fluids – We have determined that a mafic rock is the best material to use for studying thermal pore fluid pressurization, a mechanism being incorporated extensively in theoretical models of dynamic earthquake slip [*N. Lapusta and J. R. Rice*, 2004; *N Lapusta and J R Rice*, 2004; *Noda*, 2008; *Noda and Shimamoto*, 2005; *Noda et al.*, 2009; *J. R. Rice*, 2006b; *Schmitt and Segall*, 2009; *Segall and Rice*, 2006]. The silica content of this rock is low enough that weakening does not occur by the silica gel mechanism [*C. Roig Silva et al.*, 2004; *Carla Roig Silva et al.*, 2004]. The gabbro samples that we initially tried a fluid-pressurization test on turned out to be too coarse-grained for our sample size because it developed a grain-scale topography due to differences in wear resistance between the phases, and the permeability was so small that saturating the samples was impractical. The diabase we collected from the Holyoke flow in the Tilcon Corporation quarry in North Branford, Connecticut contained too many macroscopic fractures, making it difficult to core intact samples. Geologist Randy Weingart of the Luck Stone Corporation collected some diabase samples from their Leesburg, VA, quarry for us, but they turned out to have a grain size of about 1 mm, too coarse for our annular samples with their 5 mm wall thickness. Consequently this year we took a trip to a diabase dike near Frederick, Maryland and collected some samples of the fine-grained diabase that experimentalists have been using for 80 years due to its fine grain size and lack of alteration [*Adams and Gibson*, 1929; *Brace*, 1965; *Caristan*, 1982; *Kronenberg and Shelton*, 1980; *Mackwell et al.*, 1998]. None of this material remains in any of the labs of our colleagues and the original outcrop no longer exists. Fortunately the dike from which the original material was collected in 1929 extends to the north and we were able to collect suitable material from several localities. A local stone-cutter has slabbed some of our large samples and we have cored the slabs and are currently conducting some control tests on dry samples. We will use this material to determine whether we can observe weakening by thermal pressurization. Theory suggests that this mechanism should be readily accessible at the slip velocities we can attain in our high-pressure gas apparatus, using our pore-pressure system to saturate the samples.

Geophysical implications

All of the weakening mechanisms that we are studying have profound implications for the magnitude of stress-drops during earthquakes and consequently for the magnitude of strong ground shaking. The manner in which fault strength varies with displacement and rupture velocity, as well as the rate at which healing occurs as slip velocity drops behind the rupture tip, can control the mode of rupture propagation, i.e. as a crack or as a pulse. Furthermore, these data can be important for resolving questions concerning stress levels in the crust. If coseismic friction is low, and seismic data seem to constrain the magnitude of dynamic stress drops to modest values, then the tectonic stress levels must also be modest. We may have a strong crust that is nevertheless able to deform by faulting under modest tectonic stresses if the strength is overcome at earthquake nucleation sites by local stress concentrations and at other places along the fault by dynamic stress concentrations at the rupture front. Thus, understanding high speed friction is important not only for practical matters related to predicting strong ground motions and resulting damage, but also for answering major scientific questions receiving considerable attention and funding, e.g. the strength of the San Andreas fault / the heat-flow paradox, the question that ultimately is responsible for the SAFOD project.

Summary

Our experiments show that substantial reductions in shear stress can occur at slip rates faster than those usually attained in laboratory experiments, even at rates slower than typical of earthquakes and even without wholesale frictional melting. One weakening mechanism involves the formation of a thin layer of lubricating silica gel and there are reasons to believe that this mechanism may operate on natural faults as well as in our experiments. The weakening that we have attributed to flash weakening is seen in some sample assemblies and not in others. It appears that the sample assemblies that do not show the weakening are giving unreliable results and that the weakening is real and not an experimental artifact. However, more experiments are needed to verify this conclusion. Whether either the gel or the flash weakening mechanisms is important for earthquakes is still unclear, but they are certainly plausible candidates. If the large reductions in shear stress seen in our experiments are characteristic of earthquakes, it implies that dynamic stress drops may be nearly complete and that, unless the initial stress is also small, accelerations and strong ground motions should be quite large.

REFERENCES CITED

Adams, L. H., and R. E. Gibson (1929), The elastic properties of certain basic rocks and of their constituent minerals, *Proc. Nat. Acad. Sci.*, *15*, 713-724.

Beeler, N., and T. Tullis (2003), Constitutive relationships for fault strength due to flash-heating, paper presented at 2003 SCEC Annual Meeting Proceedings and Abstracts, Southern California Earthquake Center, PalmSprings, California, 2003.

Beeler, N. M., T. E. Tullis, and D. L. Goldsby (2008), Constitutive relationships and physical basis of fault strength due to flash-heating, *J. Geophys. Res.*, *113*, B01401, doi:01410.01029/02007JB004988.

Brace, W. F. (1965), Some new measurements of linear compressibility of rocks, *J. Geophys. Res.*, *70*(2), 391-398.

Caristan, Y. (1982), The transition from high temperature creep to fracture in Maryland diabase, *J. Geophys. Res.,*, *87*(B8), 6781–6790.

Di Toro, G., D. L. Goldsby, and T. E. Tullis (2004), Friction falls toward zero in quartz rock as slip velocity approaches seismic rates, *Nature*, *427*, 436-439.

Dieterich, J. H., and G. Conrad (1984), Control of time- and velocity-dependent friction in rocks by absorbed water, *J. Geophys. Res.*, *89*, 4196-4202.

Goldsby, D., and T. E. Tullis (2002), Low frictional strength of quartz rocks at subseismic slip rates, *Geophys. Res. Lett.*, *29*(17), 1844, doi:1810.1029/2002GL015240.

Goldsby, D. L., and T. E. Tullis (1997), Shear heating induced pressurization of pore fluid as a dynamic fault weakening mechanism, *Eos Trans. AGU*, *78, Fall Meeting Abs. Supp.*, 472.

Goldsby, D. L., and T. Tullis (2003), Flash heating/melting phenomena for crustal rocks at (nearly) seismic slip rates, paper presented at 2003 SCEC Annual Meeting Proceedings and Abstracts, Southern California Earthquake Center, Palm Springs, California, 2003.

Goldsby, D. L., and T. E. Tullis (2006), Flash weakening in high speed rock friction experiments, in *Radiated Energy and the Physics of Earthquake Faulting*, edited by A. McGarr, R. Abercrombie, H. Kanamori and G. Di Toro, p. in preparation.

Hirose, T. (2002), Experimental and field studies on the frictional melting along faults and implications to the earthquake generation processes, Ph.D. thesis, Kyoto Univ., Kyoto, Japan.

Hirose, T., and T. Shimamoto (2004), Growth of a molten zone as a mechanism of slip weakening of simulated faults in gabbro during frictional melting, *Journal of Geophysical Research*, submitted, paper 2004JB003207.

Kohli, A. H., D. L. Goldsby, G. Hirth, and T. E. Tullis (2011), Flash weakening of serpentinite at near-seismic slip rates, *J. Geophys. Res.*, *116*, 2010JB007833R (in press).

Kronenberg, A. K., and G. L. Shelton (1980), Deformation microstructures in experimentally deformed Maryland diabase, *J. Struct. Geol.*, *3*(2), 341-353.

Lapusta, N., and J. R. Rice (2004), Earthquake sequences on rate and state faults with strong dynamic weakening, paper presented at 2004 SCEC Annual Meeting Proceedings and Abstracts, Southern California Earthquake Center, PalmSprings, California, 2004.

Lapusta, N., and J. R. Rice (2004), Earthquake sequences on rate and state faults with strong dynamic weakening, *Eos. Trans. Am. Geophys. Union, Fall Meeting Suppl.*, *85*(47), T22A-05.

Lim, S. C., and M. F. Ashby (1987), Wear mechanism maps, *Acta Metallurgica*, *35*(1), 1-24.

Mackwell, S. J., M. E. Zimmerman, and D. L. Kohlstedt (1998), High-temperature deformation of dry diabase with application to tectonics on Venus, *J.. Geophys. Res.*, *103*(B1), 975-984.

Noda, H. (2008), Frictional constitutive law at intermediate slip rates accounting for flash heating and thermally activated slip process, *J. Geophys. Res.*, doi:10.1029/2007JB005406.

Noda, H., and T. Shimamoto (2005), Thermal pressurization and slip-weakening distance of a fault: An example of the Hanaore fault, southwest Japan, *Bull. Seis. Soc. Am.*, *95*(4), 1224-1233.

Noda, H., E. M. Dunham, and J. R. Rice (2009), Earthquake ruptures with thermal weakening and the operation of ma jor faults at low overall stress levels, *J. Geophys. Res.*, *114 (B07302)*, doi:10.1029/2008JB006143.

Prakash, V., and F. Yuan (2004), Results of a pilot study to investigate the feasibility of using new experimental techniques to measure sliding resistance at seismic slip rates, *Eos Trans. AGU, Fall Meet. Suppl.*, *85*(47), Abstract T21D-02.

Rempel, A. W., and S. L. Weaver (2008), A model for flash weakening by asperity melting during high-speed earthquake slip, *Journal of Geophysical Research - Solid Earth*, *113*, B11308, doi:11310.11029/12008JB005649.

Rice, J. R. (1999), Flash heating at asperity contacts and rate-dependent friction, *Eos Trans. AGU*, *80*, F681.

Rice, J. R. (2006a), Heating and weakening of faults during earthquake slip, *J. Geophys.Res.*, in press, doi:10.1029/2005JB004006.

Rice, J. R. (2006b), Heating and weakening of faults during earthquake slip, *Journal of Geophysical Research-Solid Earth*, *111*(B5), doi:10.1029/2005JB004006.

Roig Silva, C., D. L. Goldsby, G. D. Toro, and T. E. Tullis (2004), The role of silica content in dynamic fault weakening due to gel lubrication, *Eos. Trans. Am. Geophys. Union, Fall Meeting Suppl.*, *85*(47), T21D-07.

Roig Silva, C., D. L. Goldsby, G. Di Toro, and T. E. Tullis (2004), The role of silica content in dynamic fault weakening due to gel lubrication, paper presented at 2004 SCEC Annual Meeting Proceedings and Abstracts, Southern California Earthquake Center, Palm Springs, California.

Schmitt, S. V., and P. Segall (2009), Thermal pressurization during “slip law” frictional earthquake nucleation, *Poster, 2009 SCEC Annual Meeting*.

Segall, P., and J. R. Rice (2006), Does shear heating of pore fluid contribute to earthquake nucleation?, *Journal of Geophysical Research-Solid Earth*, *111 (B09316)*, doi:10.1029/2005JB004129.

Stel, H. (1981), Crystal-growth in cataclasites - diagnostic microstructures and implications, *Tectonophysics*, *78*(1-4), 585-600.

Stel, H., and A. C. Lankreyer (1994), Flow and deformation of viscous, silica-oversaturated dispersoins in low-grade faults, *J. Struct. Geol.*, *16*(3), 303-313.

Titone, B., K. Sayre, G. Di Toro, D. L. Goldsby, and T. E. Tullis (2001), The role of water in the extraordinary frictional weakening of quartz rocks during rapid sustained slip, *Eos Trans. AGU*, *82*, T31B-0841.

Tsutsumi, A., and T. Shimamoto (1997), High-velocity frictional properties of gabbro, *Geophys. Res. Lett.*, *24*, 699-702.

Tullis, T. E., and D. L. Goldsby (2003), Flash melting of crustal rocks at almost seismic slip rates, *Eos. Trans. Am. Geophys. Union, Fall Meeting Suppl.*, *84*(46), Abstract S51B-05.

Yuan, F., and V. Prakash (2005), Sliding resistance rocks and analog materials at seismic slip rates and higher, paper presented at 2005 SCEC Annual Meeting Proceedings and Abstracts, Southern California Earthquake Center, Palm Springs, California.